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Kinematics of assisted and unassisted plyometric training of vertical jumping and rebounding in youth male football players – A six-week training study

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Abstract: The purpose of this study was to compare the kinematics of assisted and unassisted plyometric training of vertical jumping and rebounding activities following a six-week training intervention. 13 youth males from a professional football academy completed six weeks of either unassisted (n = 6) or band-assisted (n = 7) plyometric training sessions twice a week during their competitive season. Pre- and post-assessments of counter-movement jump (CMJ) height, 50 cm drop-jump (DJ_{50}) ground contact time (GCT), jump height and reactive strength index (RSI), and submaximal-hopping (SMH) GCT, jump height and RSI were compared. Pre- and post-assessment ankle angle at touch-down (TD), peak flexion (PF) and mid-flight (MF) were also analysed for the submaximal-hop test only. Following training, significant main effects of time were observed for CMJ height, DJ_{50} GCT and MF ankle angle ($p < 0.05$) and a significant effect of group was observed for DJ_{50} RSI ($p < 0.05$). These results suggest that both unassisted and assisted plyometric training may be useful for enhancing the kinematics and technical performance of plyometric activities in a youth male football population.

Keywords: Assisted plyometric training, unassisted plyometric training, youth football, kinematics

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1. Introduction

Plyometric training is widely used in athletic development and it has been associated with various musculoskeletal, neuromuscular and performance adaptations [1], specifically: improved vertical [2-6] and horizontal [3-5] jump ability, enhanced sprint and agility performance [2-4, 7], increased endurance [3, 5], and injury risk reduction [8]. These adaptations would likely benefit performance in team-sports such as football, where aerial duels for possession occur frequently and straight line sprinting is the most common performance action that precedes a goal being scored [9]. As such, plyometric training is often employed in strength and conditioning programes for football. Chelly *et al*., [2] examined the effects of an eight week plyometric training programme with a group of adult male football players and observed significant increases in squat jump (SJ) height ($p < 0.01$), countermovement jump (CMJ) height ($p < 0.01$) and various sprint velocities ($p < 0.01$). A more recent study by Ramirez-Campillo *et al*., [10] also observed significant improvements in CMJ height ($p < 0.05$), as well as broad jump ($p < 0.05$) and drop-jump ($p < 0.05$) performance in a sample of youth male soccer players following a six-week plyometric training intervention, but noted that these were exclusive to the post-peak height velocity (PHV) athletes included in the study. In contrast, other studies have reported improved jump and sprint performance in pre-PHV [11, 12] and mid-PHV [11] soccer players in response to plyometric training. Additional performance adaptations, including improvements in a change of direction ability, balance, kicking velocity and endurance have been reported following six weeks of combined vertical and horizontal plyometric training in youth football athlete populations [3, 4].

These adaptations may be attributed to various factors, including increased agonistic neural drive, improved inter-muscular coordination, enhanced stretch reflexes, altered mechanical properties of the plantar flexor muscle-tendon complex, changes in muscle size and architecture, and changes in single fibre mechanics [1]. Accordingly, McKinlay *et al*., [13] reported increased knee extensor isometric peak torque and rate of peak torque development in addition to increased vastus lateralis thickness following eight weeks of plyometric training in youth male soccer players. The authors suggested that some of the aforementioned neuromuscular factors, in combined with the measured muscle morphological adaptations, contributed to the observed performance adaptations. Although a large body of evidence exists examining the various adaptations associated with plyometric training, research confirming what underpins skilled plyometric performance and how to develop this in youth athletic populations optimally is conspicuous by its absence.

Plyometric training involves the performance of movement tasks that utilise musculotendinous stretch-shortening cycles (SSCs), whereby rapid concentric actions are preceded by high intensity eccentric actions and a brief amortisation phase. The eccentric action can enhance the force output of the subsequent concentric action due to a number of contributing factors, including: an increase in the range of movement throughout which muscle force is being produced, reflex potentiation, and the storage and release of elastic energy [14]. According to the three component muscle model proposed by Hill [15], elastic energy can be generated in the series elastic (tendinous structures), parallel elastic (connective tissues) and contractile elements (actin-myosin cross-bridges) of the muscle tendon unit when stretched. Evidence for the enhancement of force output due to the release of this elastic energy can be found in the observation that greater jump heights can be achieved using CMJs in comparison to SJs [16]. Despite this, some authors dispute the role of elastic energy in human movement, suggesting that the other aforementioned factors, primarily the increase in time available to develop muscle force, are responsible for the enhanced force outputs seen with activities involving counter-movements [17]. However, greater jump heights have been observed following CMJs in comparison to SJs preceded by an isometric contraction [18], demonstrating the potential importance of elastic energy return in plyometric training.

To ensure effective elastic energy reutilisation, the time between the eccentric and concentric action must be brief, a delay would result in the potential energy dissipating as heat. During plyometric rebounding activities, such as drop-jumps (DJs) and hopping, this means achieving a short transition between landing and take-off, or, ground contact time (GCT), while still attempting to maximise force expression. Arampatzis *et al*. [19] compared depth jumped at different heights and observed that GCTs and leg stiffness were inversely related, suggesting that achieving a short GCT requires a stiff ground contact. Specifically, ankle joint stiffness has been reported to be the key determinant of overall leg stiffness during plyometric hopping tasks in numerous studies [20, 21]. There are multiple factors that may contribute to the adjustment of joint stiffness. With regards to regulating overall leg stiffness, researchers have observed that this can be achieved by increasing the activity of their lower-limb muscles prior to ground contact [19]. Pre-activity of the lower-limb musculature may help to ensure that, during the eccentric phase of a rebound landing, the majority of the stretch occurs within the series elastic element of the muscle-tendon unit. This would be advantageous to performance as tendons have a greater capacity for elastic energy storage and release in comparison to muscle [22]. As well as this, the muscles acting relatively isometrically allows a greater force output to be achieved [14]. However, there is evidence that shows that the EMG activity of the plantar-flexors does not acutely alter ankle stiffness during hopping [21], bringing into question the importance of the magnitude of muscle activity in adjusting ankle stiffness. Rather, the timing and coordination of muscle activity, specifically an increase in co-activation of both plantar- and dorsi-flexors prior to and during the initial stages of ground contact, could play a role in enhancing ankle joint stiffness during plyometrics, hence the development of motor-coordination skill. This phenomenon has been observed during running at increasing speeds [23], although not during a repetitive hopping task [24], where agonistic pre-activation and an augmented stretch-reflex response were proposed as being of greater importance for stiffness regulation. It has also been suggested that changes in ankle kinematics may contribute to regulating ankle stiffness [21]. Indeed, Cappa and Behm [25] compared forefoot landings versus flat-foot landings, where the heel contacts the floor, on DJ and hurdle-jump performance and found that a forefoot landing strategy was associated with a shorter GCT, greater ground reaction force, enhanced stiffness and a higher rate of force development. One mechanism for how ankle kinematics may affect ankle stiffness is a reduction in Achilles tendon slack with increasing dorsiflexion. Muraoka *et al.* [26] suggested that a decrease in tendon slack between -30° and -10° of dorsiflexion contributed to a 20% reduction in electromechanical delay, which could be an important factor in reducing GCT during plyometric training. Despite some discrepancies in the literature, it seems that a combination of both kinematic and kinetic factors feed into adjusting ankle stiffness, and therefore leg stiffness, and therefore plyometric effectiveness.

When coaching plyometrics, athletes are often encouraged to land with a flatter foot contact, without the heel touching the floor, to allow for an aggressive plantar-flexion action through an increased range of motion following landing. This requires the athlete to actively dorsi-flex the foot during flight in preparation for ground contact and coordinating this pattern forms an essential component of plyometric skill [27]. As with developing any other motor skill, athletes must progress through various stages of learning during the transition from novice to expert performer. According to Fitts and Posner's [28] model, three stages of learning exist: cognitive, associative and autonomous. During the early cognitive stage, novice performers must devote substantial attention to the performance of a particular skill, which often results in "slow, non-fluent, and error prone movement execution" [29]. This poses an issue within the context of plyometric skill development as a limited window of opportunity exists during the flight to prepare for subsequent ground contact, and therefore traditional plyometric training may not afford novice performers the opportunity to generate sufficient flight time to develop the plyometric skill.

Assisted plyometric training may offer an alternative means of developing plyometric skills, whereby the athlete has greater time to coordinate preparing for ground contact. Assisted plyometric training refers to the performance of plyometric activities with the application of external assistance, typically from elastic bands or tubing [30]. Compensation can also be achieved using buoyancy during water-based plyometrics [31] or from the elastic recoil of a trampoline surface [32], however, these modalities appear to be less commonly utilised. There are multiple potential rationales for incorporating assisted plyometric training into a strength and conditioning programme including to reduce ground reaction force for load-compromised rehabilitating athletes [33], as a potentiating stimulus for body-weight jumping [34], or to increase movement velocity to serve as a supramaximal 'over-speed' training stimulus [7]. A number of researchers have compared the effects of a period of assisted and unassisted plyometric training on numerous performance measures. Sheppard *et al.* [35] exposed junior national volleyball players to five weeks of thrice-weekly assisted or unassisted jump training. They observed that the assisted plyometric training (APT) group significantly improved CMJ and vertical spike-jump height, whereas the unassisted plyometric training (UPT) group did not ($p < 0.05$). While this may advocate the use of APT over UPT, it is essential to note that the protocol utilised an absolute assistance of 10 kg, resulting in different levels of relative assistance between participants. Besides, the participants were well experienced with UPT and therefore, the novelty of the assisted plyometric training stimulus may have contributed to the discrepancy in the observed training effects between groups. Makaruk *et al*., [36] utilised relative assistance of 10% bodyweight during five weeks of assisted DJ training with a population of male collegiate athletes. They observed that both UPT and APT was effective for enhancing 30 and 60 cm drop-jump height and reactivity. However, the difference in improvement between groups was only significant ($p < 0.05$) for 60 cm DJ reactivity. The lack of difference in training effects between the groups may have been due to a relatively low level of assistance. Tran *et al*., [37] reported that take-off velocity was only enhanced relative to unassisted jumping with 30 and 40% assistance than 10 and 20% assistance, although jump height was significantly increased in all conditions ($p < 0.05$). Given that the adaptations associated with over-speed training (decreased antagonistic coactivation, increased cross-bridge cycling rates, and improved calcium kinetics) [7] are only likely to be elicited when take-off velocity is increased, this may explain why 10% body-weight assistance induced similar adaptations to UPT.

Despite evidence for the performance adaptations associated with assisted plyometric training, there is a paucity of research on how it may chronically impact on plyometric technique, specifically ankle kinematics. Acutely, body-weight support during a repetitive unilateral hopping task has not been shown to alter lower limb kinematics relative to an unassisted control in a clinically meaningful way [33], however, it is unclear whether this would be the case over a longer period of time where altering kinematics may be desirable. Therefore, the purpose of this study is to compare the kinematics of assisted and unassisted plyometric training of vertical jumping and rebounding activities in youth academy football players following a six-week training intervention.

2. Methods

2.2 An Experimental approach to the problem

Using a pre-test post-test randomised between-group comparison, 13 players were assessed for jump performance during a CMJ, DJ and submaximal hopping (SMH) test before and after a six-week assisted or unassisted plyometric training intervention. Sagittal plane ankle kinematics were also analysed for the submaximal hopping test only. The inclusion of a control group where no plyometric training was performed was considered but deemed unethical, as denying any of the participants the opportunity to participate in the plyometric training sessions may have disadvantaged their long-term athletic development.

2.2 Participants

15 male participants from a professional football academy were recruited for the present study following ethical approval from the Cardiff Metropolitan University Research and Ethics Committee. Inclusion criteria were: a) being involved in the professional football academy's under 18 football programme b) possessing no lower-limb injury within the previous six months that would prevent the safe performance of jumping activities c) having limited experience of dedicated plyometric training. All participants were involved in a full-time football programme, typically including one match, four technical training sessions, and two resistance training sessions per week. The plyometric training sessions were completed before the resistance training sessions, the content of which was standardised between groups. Football match and training load data (rating of perceived exertion [RPE] x session duration [min]) for all players was monitored for the period of the study.

Following written and verbal information regarding their involvement in the study, all participants completed a written assent form and the Physical Activity Readiness Questionnaire (PAR-Q). Parental consent forms were also obtained for all participants. Participants were familiar with the testing and training procedures one week before the pre-testing session and training intervention, respectively. During familiarisation to the testing procedures, the participants were instructed to maximise jump height for the CMJ and maximise jump height and minimise ground contact times for the DJ. The participants were instructed to hop in time with a 2.0 Hz metronome for the SMH test. For the training intervention, players were randomly assigned to either an unassisted plyometric training group (UPT; n = 6) or an assisted plyometric training group (APT; n = 7). Ramirez-Campillo *et al*., [4] reported that group sizes of at least six participants were sufficient for researching the effects of a short-term plyometric training intervention in a youth football population. Due to scheduling and injury, not all of the participants were able to attend all of the training sessions. Only participants who completed a minimum of eight sessions were included for post-testing and subsequent analysis and therefore 13 participants completed the study (age (years) = 17.1 ± 0.5; stature (cm) = 177.9 ± 5.3; body mass (kg) = 67.7 ± 5.0). This threshold was selected based on the research of Argus *et al.*, [38] who reported improvements in vertical jump performance following four weeks of twice-weekly assisted plyometric training in combination with regular training activities in a group of professional rugby union players. The descriptive characteristics of each training group are presented in Table 1.

2.3 Testing procedures

All testing sessions were preceded by a minimum of 24 hours rest from arduous physical activity to minimise the impact of fatigue on testing performance. Standing participant stature was measured to the nearest 0.1 cm using a portable stadiometer (Seca 213, Seca Ltd, Birmingham, United Kingdom). Body mass was measured to the nearest 0.1 kg using a set of digital scales (Seca 803, Seca Ltd, Birmingham, United Kingdom). Before the vertical jump testing, all participants completed a standardized warm-up in-line with a RAMP protocol. The warm-up protocol is summarised in Table 2.

Table 1 Descriptive characteristics of UPT and APT training groups.

	UPT (n = 6)	APT (n = 7)	p
Age (years)	17.2 ± 0.7	17.1 ± 0.4	0.62
Stature (cm)	177.1 ± 5.1	178.7 ± 5.8	0.61
Body Mass (kg)	66.9 ± 3.9	68.4 ± 5.9	0.61
sRPE training load (AUs)	19297 ± 5771	25132 ± 4343	0.06

Data expressed as mean ± SD. UPT: unassisted plyometric training group; APT: assisted plyometric training group; sRPE: session rating of perceived exertion; AUs: arbitrary units; SD: standard deviation

Table 2 RAMP warm-up protocol.

Exercise	Volume
Static cycling	3 minutes
Mini-band squat	10 repetitions
Alternate lunge	10 repetitions per leg
Single-leg Romanian dead-lift	10 repetitions per leg
Standing adductor swing	10 repetitions per leg
Counter-movement jump	3 repetitions at 50% perceived maximal effort
	3 repetitions at 75% perceived maximal effort
	3 repetitions at 90% perceived maximal effort

Table 3 Outline of the intervention protocol.

Exercise	Volume (sets x repetitions)		
	Weeks 1-2	Weeks 3-4	Weeks 5-6
Bilateral hops	5 x 10	5 x 10	5 x 10
Counter-movement jumps	3 x 5	4 x 5	5 x 5
30 cm drop-jumps	3 x 5	4 x 5	5 x 5
Total foot contacts	80	90	100

2.3.1 Vertical jump testing

Upon completion of the warm-up protocol, the participants completed three repetitions of a CMJ on a pair of portable force plates (PASCO, Roseville, CA, USA) and three repetitions of a 50 cm drop-jump (DJ_{50}) and one set of 20 SMHs in time with a metronome set at 2.0 Hz on a portable contact mat (SmartJump, Fusion Sport, Australia). Participants were required to repeat the SMH test if the researchers were unsatisfied with the level of synchronicity to the metronome. Throughout all tests, the participants were instructed to keep their hands on their hips.

2.3.2 Biomechanical analysis

Before the warm-up, five reflective markers were placed on the following anatomical landmarks on the participant's left side: fifth metatarsophalangeal joint, lateral malleolus, and lateral femoral epicondyle, greater trochanter and acromion process. This allowed for the analysis of joint angles at the: ankle, knee and hip. A tablet camera (iPad Mini 4, Apple, Cupertino, CA, USA) was placed three metres away from where the jumps were performed in the sagittal plane. All video footage was recorded at a frame-rate of 30 Hz.

2.4 Training

Both the UPT and APT performed six weeks of twice-weekly plyometric training at the start of their resistance training sessions. Exercise selection and training volume was standardised across conditions. A progressive volume-based overload approach was adopted, as this has been shown to be superior for enhancing vertical jump, acceleration, change of direction and endurance performance in a group of youth football players [4] in comparison to a constant volume approach. The volume of foot contacts per session was based on the recommendations of Potach and Chu [39]. An outline of the training protocol can be found in Table 3.

2.4.1 Assistance

The APT performed all jumping activities with external assistance from elastic resistance bands. The bands were placed over the top of a cross-bar of a squat rack (Figure 1A). The participants held the band(s) through the loops created and pulled the band so that their left and right first metacarpophalangeal joints were in contact with their left and right nipples, respectively (Figure 1B).

Table 4 Summary of bands utilised by each participant during the training intervention.

Participant Number	Band(s)	Body mass unloading (%)						CV (%)
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	
1	R x1	18.2	18.5	17.0	18.7	17.7	18.0	3.8
2	O x2	20.9	20.9	20.6	19.8	20.5	20.5	2.2
3	R x1	18.6	19.5	18.7	18.4	18.7	18.8	2.2
4	R x1	21.2	22.6	20.8	19.7	20.7	21.0	5.0
5	R x1	20.5	21.2	20.5	21.7	21.8	21.1	3.0
6	R x1 O x1	17.9	16.2	16.9	17.3	17.7	17.2	3.9
7	R x1	20.2	20.4	20.1	20.1	20.5	20.3	0.9

CV: coefficient of variation; O: orange band; R: red band.

Table 5 Coaching cues utilised during the intervention.

Cue	Desired outcome	Internal/external
"Pull your toes up"	Increase dorsiflexion during flight	Internal
"Bounce off the floor like a ball"	Reduce ground contact time	External
"Keep your feet underneath you"	Prevent athlete from flexing the hip during flight	Internal
"Tense your quads and glutes"	Minimise knee and hip flexion during ground contact	Internal
"Push the floor away"	Aggressively plantarflex on ground contact	External

Figure 1. **A**: Example band set-up for the APT intervention; **B**: Example participant set-up for the APT intervention. APT: assisted plyometric training.

This approach was selected on the basis of being more practical with regards to participant comfort and has also been shown to better enhance CMJ flight time with 10 and 20% bodyweight assistance in comparison to utilizing a harness [40]. Prior to the first training session, the participants in the assisted plyometric training group trialed different combinations of elastic bands to achieve a body mass unloading of approximately 20% as established using a set of digital scales (Seca 803, Seca Ltd, Birmingham, United Kingdom). Once the band(s) was selected, the participants performed multiple trials of the band set-up to assess the reliability of the percentage unloading achieved. A summary of the bands used by each participant in the APT is presented in Table 4.

2.4.2 Cueing

Cueing during the training intervention was standardised across conditions. A combination of internal and external cues, as well as visual demonstrations, was utilised as, although external cues have been suggested to be superior for novice motor skill development [41], achieving some of the desired kinematic changes required internal coaching cues.

A summary of the coaching cues used can be found in Table 5.

2.5 Data analysis

From the testing data, a number of independent variables were selected for analysis. With regards to vertical jump performance, jump heights (cm) for all three tests and GCT (s) and reactive strength index (RSI) (mm.s^{-1}) for the drop jump and submaximal hopping test were included. CMJ jump height was derived from the vertical force data utilising the method previously described by Chavda *et al.*, [42] For the CMJ, each participant's repetition with the greatest jump height was included for analysis. For the DJ_{50}, each participant's rehearsal with the greatest RSI was included for analysis. A mean average of the data recorded for all dependent variables was calculated from repetitions 6-15 for the SMH test and was included for analysis.

For the ankle biomechanics, ankle angle (°) at three phases: touch-down (TD), peak flexion (PF) and mid-flight (MF) were calculated and included for analysis. The definition of each of these phases can be found in Table 6. The video footage was digitised and analysed using Kinovea version 0.8.15 (Kinovea open source project, www.kinovea.org), which has previously been shown to be reliable for ankle angle analysis during walking [43].

2.6 Statistical analysis

Mean averages and standard deviations (SDs) were calculated for all measurement variables. All data were assessed for normality using Shapiro-Wilk tests. Standardised mean effect sizes were calculated for comparison to previous research, where required. All dependent variables were compared between groups (n = 2) and across time-points (n = 2) using a 2x2 mixed model ANOVA. Statistical significance was accepted at $p < 0.05$. All statistical analyses were completed using SPSS version 24 (SPSS Inc., Chicago, IL, USA).

Table 6 Kinematic phase definitions.

Phase	Volume
Touch-down	The first frame in which the participant is deemed to be in contact with the floor following flight
Peak flexion	The frame in which the most acute ankle angle was achieved during ground contact
Mid-flight	The frame in which vertical velocity is deemed to be approximately zero during flight

3. Results

3.1 Counter-movement jump

The 2-way mixed model ANOVA revealed a significant main effect of time ($F_{1,11} = 58.63$, $p < 0.01$, ηp2 = 0.84) on CMJ height, with an increase between pre- and post-intervention from 26.3 ± 4.6 cm to 39.6 ± 7.6 cm and 27.1 ± 7.4 cm to 37.3 ± 2.3 for the APT and UPT, respectively (Figure 2). The main effect of group, however4.67, was non-significant ($F_{1,11} = 0.07$, $p > 0.05$, ηp2 = 0.01), with both groups performing similarly during both testing sessions. The interaction effect between time and group was also non-significant ($F_{1,11} = 1.01$, $p > 0.05$, ηp2 = 0.08), suggesting that the change in mean CMJ height between the two testing sessions were comparable for the APT and UPT. It is important to note, however, that the post-intervention data violated the assumption of homogeneity of variance.

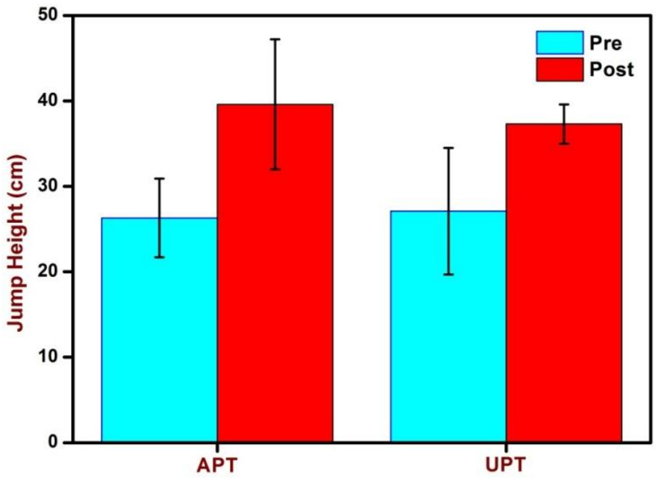

Figure 2 Mean ± SD CMJ height for the APT and UPT pre- and post-intervention. APT: assisted plyometric training group; UPT: unassisted plyometric training group; SD: standard deviation.

3.2 Drop-jump

Mean values for the DJ_{50} GCT, jump height and RSI pre- and post-intervention for the UPT and APT are displayed in Table 7. The results of the 2-way mixed model ANOVAs revealed a significant main effect of time for GCT ($F_{1,11} = 7.28$, $p < 0.05$, ηp2 = 0.40), with both the APT and UPT displaying a pre- to post-intervention decrease from 278 ± 91 to 242 ± 60 ms and 222 ± 28 to 171 ± 29 ms, respectively. The main effect of group for GCT approached but did not achieve statistical significance ($F_{1,11} = 4.67$, $p = 0.054$, ηp2 = 0.30). A significant main effect of group for RSI ($F_{1,11} = 4.99$, $p < 0.05$, ηp2 = 0.31) was observed, with the UPT achieving a greater mean RSI in comparison to the APT pre- and post-intervention. Whilst the interaction effect between group and time for mean RSI did not reach statistical significance ($F_{1,11} = 3.72$, $p = 0.08$, ηp2 = 0.25), it is noteworthy that the UPT displayed an increase from 1.59 ± 0.46 to 1.98 ± 0.36 $mm.ms^{-1}$, whereas the APT displayed a slight decrease from 1.36 ± 0.44 to 1.34 ± 0.29 $mm.ms^{-1}$.

No statistically significant effects were observed for mean jump height, despite decreases observed in both groups (Table 7). Overall these data suggest that both training interventions were effective for reducing DJ_{50} GCT but had negative, albeit non-significant, effects on jump height, which may have been sufficient to prevent statistically significant changes in RSI from occurring.

3.3 Sub-maximal hop test

3.3.1 Ankle kinematic analysis

The mean ankle angle at TD, PF and MF for the UPT and APT groups are displayed in Table 8. For the MF ankle angle there was a statistically significant main effect of time ($F_{1,11} = 6.577$, $p < 0.05$, ηp2 = 0.37) (Figure 3), with decreases in MF ankle angle observed in both groups. The effect of group and the interaction between the two variables were non-significant ($p > 0.05$), suggesting that the ankle angles are seen and the magnitude of change pre- to post-intervention were similar across conditions.

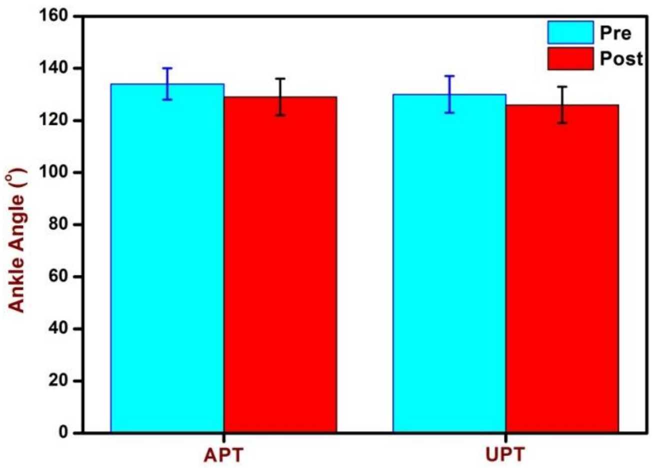

Figure 3 Mean ± SD ankle angle at the mid-flight phase during submaximal hopping test for the APT and UPT pre- and post-intervention. APT: assisted plyometric training group; UPT: unassisted plyometric training group; SD: standard deviation.

For the TD and PF phases, no significant effects were observed ($p > 0.05$). Overall, these data suggest that both interventions were similarly effective for inducing substantial changes in the degree of dorsiflexion achieved MF but that neither impacted the kinematic variables observed during the phases associated with ground contact.

3.3.2 Kinematic analysis

Mean values for the SMH GCT, jump height and RSI for the UPT and APT groups are displayed in Table 9. Despite reductions in GCT and increases in jump height and RSI for both groups, the 2-way mixed model ANOVA revealed non-significant main and interaction effects ($p > 0.05$) for all three variables, with both groups achieving similar results during both testing sessions (Table 8). Only the pre-intervention jump height data violated the assumption of homogeneity of variance.

Table 7 Mean ± SD DJ_{50} GCT, JH and RSI for the UPT and APT pre- and post-intervention.

	GCT (ms)		JH (cm)		RSI ($mm.ms^{-1}$)	
	Pre	Post	Pre	Post	Pre	Post
UPT	222 ± 28	171 ± 29	34.4 ± 5.9	33.2 ± 3.1	1.59 ± 0.46	1.98 ± 0.36
APT	278 ± 91	242 ± 60	35.0 ± 5.3	31.5 ± 4.9	1.36 ± 0.44	1.34 ± 0.29

UPT: unassisted plyometric training group; APT: assisted plyometric training group; GCT: ground contact time; JH: jump height; RSI: reactive strength index; SD: standard deviation.

Table 8 Mean ± SD SMH ankle angle at the TD, PF and MF during submaximal hopping for the UPT and APT groups.

	TD (°)		PF (°)		MF (°)	
	Pre	Post	Pre	Post	Pre	Post
UPT	123 ± 7	121 ± 9	98 ± 5	97 ± 5	130 ± 7	126 ± 7
APT	128 ± 7	129 ± 6	101 ± 8	99 ± 2	134 ± 6	129 ± 7

UPT: unassisted plyometric training group; APT: assisted plyometric training group; TD: touch-down phase; PF: peak flexion phase; MF: mid-flight phase; SD: standard deviation.

Table 9 Mean ± SD SMH GCT, JH and RSI for the UPT and APT pre- and post-intervention.

	GCT (ms)		JH (cm)		RSI ($mm.ms^{-1}$)	
	Pre	Post	Pre	Post	Pre	Post
UPT	173 ± 32	160 ± 10	13.3 ± 2.7	14.4 ± 0.8	0.82 ± 0.30	0.91 ± 0.10
APT	167 ± 17	160 ± 9	14.2 ± 1.2	14.3 ± 1.1	0.86 ± 0.15	0.90 ± 0.11

UPT: unassisted plyometric training group; APT: assisted plyometric training group; GCT: ground contact time; JH: jump height; RSI: reactive strength index; SD: standard deviation.

4. Discussion

The results of the present study suggest that both APT and UPT were effective for improving some of the variables associated with CMJ, DJ and SMH performance, although neither modality appeared to be superior to the other.

The significant main effect of time on CMJ height suggests that both APT and UPT can induce positive effects with regards to vertical jump performance. This would likely benefit football performance as vertical jumping frequently occurs during aerial contests for possession of the football. Similar effects have also been observed in youth football populations, with Thomas *et al.*, [6] reporting moderate (0.7) and large (1.1) effect sizes following six weeks of unassisted CMJ and DJ training, respectively. The larger effect sizes observed within the present study (APT = 2.1; UPT = 1.9) may suggest that a combined slow- and fast-SSC training protocol provides a greater training stimulus for improving CMJ height, although smaller effect sizes to that of Thomas *et al.*, [6] have previously been reported with a similarly combined approach [4]. Alternatively, the greater effect sizes may have been attributable to a relatively lower plyometric training age for the participants in the present study, although the plyometric training experience of the participants utilised in the aforementioned study was not explicitly stated.

Positive training adaptations with regards to CMJ height have also been reported with a number of APT programmes with sample populations ranging from male junior elite jump sport athletes [35] to recreationally trained males [44]. It has been previously suggested that APT may be superior for enhancing CMJ height in comparison to UPT [38] due to an induced over-speed stimulus. The lack of difference between the APT and UPT groups with regards to the improvements in jump height in the present study may have been due to insufficient assistance for the APT group. Previous research has shown that take-off velocity is only enhanced with assistance greater than 30% bodyweight [37]. Given that the targeted assistance in the present study was 20% bodyweight, the APT group may not have benefited from the training adaptations associated with over-speed training. Similarly, the superiority of APT over UPT has only tended to be observed within well-trained subjects [35, 38] and may simply have been reflective of a novel training stimulus for athletes with extensive UPT experience. This may also explain why no differences were observed between the two groups with regards to CMJ height adaptations in the present study, as both had limited UPT experience.

The observed reductions in DJ_{50} GCT for both the APT and UPT groups demonstrates that both training modalities are capable of eliciting adaptations associated with enhanced SSC function or plyometric ability. Makaruk *et al.*, [36] also shown similar effects, with five weeks of thrice-weekly assisted or unassisted DJ training reported to improve GCT during a DJ_{30} test. However, whereas in the present study, no significant effects were found for RSI or jump height, they observed improvements in these variables, albeit utilising a lower drop height. Interestingly, they found that when the drop height was increased to 60 cm, only the APT significantly reduced GCT. In contrast, there were no significant group or interaction effects concerning GCT in the present study, suggesting both interventions resulted in similar adaptations. The reductions in GCT are likely attributable to primarily neural adaptations, given the short duration of both protocols. It has previously been suggested that increased motor-unit recruitment and pre-activation of lower limb musculature, enhanced reflex control, and a reduction in co-contraction contribute to SSC development in youth athletes [45] and may have been responsible for the adaptations observed in the present study. These could enhance both the magnitude and rate of force development, both of which are critical components for plyometric ability where maximising jump height and minimising GCT are desirable. However, it is not possible to rule out the potential for structural adaptations within the muscle-tendon unit contributing to the observed changes. Kubo *et al.*, [46] exclusively attributed the observed jump height improvements in a range of vertical jumping activities, including drop-jumps, to increases in tendon and joint stiffness, as plantar- and dorsi-flexor muscle activity was unchanged. However, this training was carried out for a longer duration (12 weeks) with a higher weekly training frequency (4 days.week^{-1}).

Despite the reductions in GCT, the only significant effect on RSI was the main effect of the group with the UPT achieving greater RSI scores during both the pre- and post-test. The lack of a significant time or interaction effect with respect to RSI, may have been due to the reduction in jump height for both the APT and UPT. The reduction in mean jump height was greater for the APT (3.5 cm) in comparison to the UPT (1.2 cm). This may have been due to the lower mechanical load associated with APT resulting in a less potent training stimulus. Bodyweight assistance values of 20% have been shown to reduce peak impact force following a CMJ, potentially reducing the eccentric demand and, therefore, adaptations associated with this type of muscular contraction [38].

It is possible that the reduction in jump height may have been reflective of the participants adopting an alternate DJ strategy favouring reduced GCTs over greater jump heights. During plyometric activities, there exists a trade-off between GCT and jump height, as generating more significant vertical impulses to jump higher would require more time on the ground if RFD or elastic energy reutilisation is unchanged. Based on previous research [47], it is possible that the cueing utilised in the present study put a greater emphasis on reducing GCT. Still, the participants did not sufficiently enhance the neuromuscular qualities required to do this while increasing or even maintaining jump height. However, with regards to the longer-term adaptations associated with the APT and UPT utilised in the present study, this shift towards reduced GCTs over maximised jump heights may have aligned the participants more closely with that of the ideal technical model for DJ performance [48]. If it were to be progressed with appropriate increases in training intensity and/or volume, one could speculate that increases in jump height may occur at a later stage.

The mean MF ankle angle decreased for both the APT and UPT with a significant main effect of time observed. This indicates that the participants were able to achieve increased ranges of dorsiflexion during the flight phase, which may be of benefit to plyometric performance as it results in a more excellent range of motion through which to actively plantar-flex immediately before and during ground contact [22]. To achieve this increase in dorsiflexion the muscular activity of the tibialis anterior was likely increased. Co-activation of both the plantar and dorsi-flexor musculature during flight could contribute to producing a stiffer ground contact [22]. The dorsiflexion change could also affect SSC function by reducing Achilles tendon slack, provided the dorsiflexion can be maintained during the descent of the flight phase. Reductions in tendon slack have been shown to enhance force transmission through the MTU and reduce the electromechanical delay associated with the subsequent concentric action [26], which would contribute to an enhanced plyometric action. The non-significant interaction effect observed for the MF angle suggests that both groups responded in a similar way to the training. It was hypothesised that utilising APT to enhance flight time may afford the greater time to focus on preparing for ground contact and may induce more favourable kinematics to a greater extent than UPT. During one of the intervention training sessions, CMJ flight time was quantified for the APT group with and without band assistance. The assisted condition was associated with a mean ± SD increase in CMJ flight time of 19 ± 9 ms. Whilst it is unclear how the level of assistance utilised affected the flight times achieved during the DJ and repeat-hop elements of the training protocols, the results of the present study may indicate that it was not sufficient to provide a greater training stimulus to develop plyometric skill versus UPT. A greater level of assistance may be required to provide a further increase in flight time to afford inexperienced athletes the opportunity to develop an enhanced technical model for the skill of SMH.

Neither the ankle angle during the TD and PF phases changed as a result of either training protocol. This suggests that, despite displaying a reduction in MF ankle angle, the participants were not able to maintain a relatively more dorsiflexed foot on touch-down and therefore, may not have benefitted from the aforementioned increased muscle pre-activation and reduced Achilles tendon slack. The PF ankle remaining unchanged indicates that the participants were not able to produce a stiffer ground contact during post-testing. While some degree of lower-limb eccentric flexion during ground contact is vital to enhance the subsequent concentric extension action [16], an excessively compliant action could reduce plyometric effectiveness due to reduced elastic energy reutilization [1]. It is important to note however that the TD and PF ankle kinematics were not adversely affected by APT and therefore its inclusion as a training modality to provide training variability or reduce mechanical load and/or psychological stress during rehabilitation or a period of de-loading, such as a competition taper, should not be overlooked. The lack of change in ankle kinematics during TD and PF for both the APT and UPT groups may be responsible for the non-significant effects observed for all of the kinematic variables analysed during the SMH. In contrast to the present study, previous research has shown that four weeks of twice-weekly UPT can significantly improve SMH leg stiffness within 12- and 15-year-old male youths, although only the 12-year-old participants achieved a significant improvement in RSI [49]. These data, in conjunction with the results of the present study, highlight potential inconsistencies with regards to the kinematics of plyometric training of SSC activities, which may warrant further research.

A number of limitations within the present study may have impacted the observed results and conclusions. Firstly, whilst a minimum threshold with regards to session attendance was established (n = 8), mean ± SD attendance was only 9.4 ± 1.4 sessions out of a possible 12 sessions. Similarly, the intervention lasted six weeks but it has been suggested that effective plyometric training programmes should last 10 weeks or more [50]. A longer intervention and higher level of adherence may have enhanced the observed training effects. One methodological limitation was the use of a 50 cm box for the DJ testing. It has been suggested that using a box height that is greater than an individual's CMJ height can result in reflex inhibition and reduce plyometric effectiveness [51]. Given that none of the participants achieved a maximal jump height greater than 50 cm, it may have been more appropriate to use lower or individualised drop heights. No injuries occurred as a result of the training, which suggests that the 50 cm box was not excessive. Utilising a higher frame rate for the ankle kinematic analysis would have improved the accuracy of the biomechanical examination and should be employed for future research. The fact that the study was carried out in-season, with high training and match-loads, may have affected the participants' ability to carry out the training sessions with maximal intensity and therefore reduced the training effects observed. Finally, whilst a similar method with regards to the band assistance has been suggested to be effective for enhancing CMJ flight time, utilising a harness may have reduced the variability of the assistance generated throughout the ranges of motion for each exercise and therefore provided a more consistent stimulus [40].

5. Conclusion

Overall the results of the study indicate that both APT and UPT can both induce chronic favourable adaptations with regards to slow and fast SSC function, however contrary to some previous research neither produced superior training adaptations. This could be due to a lack of assistance with regards to the APT or the relative UPT inexperience of the participants. APT and UPT may help to shift the athlete towards a better technical model of plyometric performance emphasising shorter GCTs, which could be advantageous for chronic plyometric training adaptations. APT could also be used as an applied procedure to support variability in training, rehabilitation from lower limb injury, de-load options when a coach is looking to reduce mechanical or physiological stress or a progressive competition taper. Future research into this area could also explore the utility of APT prior to a period of UPT for the purpose of phase potentiation in populations with limited plyometric experience.

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Conflict of interest

None of the authors have any conflicts of interest to declare.